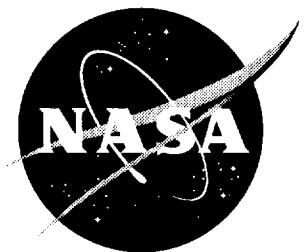


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Room Temperature and Elevated Temperature Composite Sandwich Joint Testing

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Abstract

Testing of composite sandwich joint elements has been completed to verify the strength capacity of joints designed to carry specified running loads representative of a high speed civil transport wing. Static tension testing at both room and an elevated temperature of 350°F and fatigue testing at room temperature were conducted to determine strength capacity, fatigue life, and failure modes. Static tension test results yielded failure loads above the design loads for the room temperature tests, confirming the ability of the joint concepts tested to carry their design loads. However, strength reductions as large as 30% were observed at the elevated test temperature, where all failure loads were below the room temperature design loads for the specific joint designs tested. Fatigue testing resulted in lower than predicted fatigue lives.

Introduction

Polymer matrix composite (PMC) bolted sandwich joints have been designed to transfer running axial tension loads between wing panels at specific load levels as part of the High Speed Research (HSR) Program. A single-row bolted sandwich joint was designed with the objective of transferring 5000 lb/in. and a multi-row bolted sandwich joint was designed to transfer 20,000 lb/in. The objective of the tension testing was to verify the failure mode and load levels achievable from the joint designs. Also, tension testing at 350°F was performed to evaluate the joint performances at the elevated operating temperature representative of the Mach 2.4 cruise condition. All composite facesheets were fabricated using the IM7/PETI-5 composite material system (Ref 1). The single-row specimens were constructed with 25-ply 0° dominate facesheets, a 0.5 inch thick titanium honeycomb core, and a single row of three, 0.375 inch diameter fasteners, spaced 2. inches apart. The multi-row specimens had 44-ply 0° dominate facesheets, a one inch thick titanium honeycomb core, and three rows of fasteners with three fasteners per row. The inner row of fasteners were 0.4375 inch in diameter, the center row fasteners were 0.375 inch in diameter, and the outer row fasteners were 0.3175 inch in diameter, and all fasteners were spaced 2.25 inches apart.

The multi-row bolted sandwich joint specimens were tested in two splice joint configurations. A composite honeycomb sandwich was joined with a similar composite honeycomb sandwich configuration (PMC to PMC joint), and was also joined with a Titanium joint component manufactured using the 4-sheet superplastically-formed diffusion-bonded process (SPF/DB) developed by McDonnell Douglas Corporation. The latter joint specimen is designated as the PMC to SPF/DB joint. A sketch of the PMC to PMC joint configuration is displayed in Figures 13 and a sketch of the PMC to SPF/DB joint configuration is displayed in Figure 14. Both specimen configurations were joined in a double shear design with titanium splice plates. The performance of the PMC joint could then be evaluated for two splice joint applications.

The test objectives also include verifying the fatigue strength of the multi-row bolted joint specimens. A summary of the number of composite sandwich joint specimens for each test condition

is presented in Table 1.

Table 1. Composite Joint Test Specimens

Test Conditions	Single-row Joint	Multi-row Joint	
		PMC to PMC	PMC to SPF/DB
Room temperature Static tension	1	1	1
350°F Static tension	2	1	1
Room temperature Fatigue ($R=-0.1$)	0	1	1

All testing was conducted in the Thermal Structures Lab at NASA Langley Research Center. The composite test specimens were designed and fabricated at Northrop-Grumman Corporation. The SPF/DB specimen component was designed and fabricated at McDonnell Douglas Corporation.

Single-row Joint

The single-row joint test specimens were fabricated to be 6.0 inches wide and hence were designed to transfer 30,000 lbs applied tensile load across the joint. Three single-row joint specimens were tested to failure in tension. Specimen 1 was tested at room temperature and Specimen 2 and 3 were tested at 350°F.

The room temperature specimen was tension tested using hydraulic grips in a 220 kip test machine. A photograph of the specimen mounted in the test machine is shown in Figure 1. The load was applied to the end grip tabs of the joint specimen through the hydraulic grips using a grip pressure of 5500 psi. The test machine was set in stroke control and a displacement rate of 0.01 in/min was used to apply the load to the joint specimen. The applied load versus ram displacement is plotted in Figure 2. The first indication of initial damage was observed at 31 kips, where a 10% reduction in the load was recorded and a cracking noise was heard. Subsequently, loading of the joint continued until an ultimate load of 40 kips was obtained. At the ultimate load, a 10 kip reduction in the load was observed, and the test was stopped. Since the first load reduction was less than 20%, which was considered in this test to indicate ultimate failure, the load of 40 kips was considered the ultimate failure load. The measured back-to-back strains from strain gauges, SG3 and SG4, located at the center of the specimen, are plotted in Figure 3 with the applied load. The location of SG2, SG4, and SG6 can be observed in Figure 1, where SG1, SG3, and SG5 correspond to the same locations on the opposite facesheet, respectively. The strains measured from SG1 and SG2 are plotted in Figure 4 with the applied load. At the ultimate failure load of 40 kips, a maximum strain of 2530 $\mu\text{in./in.}$ was measured at SG4 in the center of the specimen and a minimum strain of 1944 $\mu\text{in./in.}$ was measured at SG2. Examination of the specimen after testing to failure showed bearing damage at all three bolt hole locations in the composite sandwich specimen. A photograph indicating the bearing damage is given in Figure 5. Later inspection of the specimen also revealed a confined area of delamination in the composite laminate, in the neck down region to the grip end.

The elevated temperature specimens were modified to allow for a pinned connection to introduce the load and use of an existing oven in the 110 kip test machine. A one inch diameter hole was drilled in the center on the composite grip end tab and a 1.25 inch diameter hole was drilled in the metallic grip end tab to allow for the pin connections on each specimen. The oven enclosed both the specimen and fixturing as shown in Figure 6. Prior to heating the specimen in the oven, coupon samples of the fiberglass material that was bonded to the composite grip ends were heated in an oven to 350°F. The fiberglass is used to protect the composite from damage when hydraulic grips are used and there were concerns that the fiberglass material might burn at this test temperature. No material changes were observed when the fiberglass coupons were heated nor when the joint specimens with the fiberglass tabs bonded to the composite material were heated. Eight thermocouples were mounted on the composite specimen, four on each facesheet. The specimens were heated to approximately 350°F while the test machine maintained a load of approximately 200 lbs on the specimens. Temperature variations were minimal and all temperature measurements ranged between 348°F and 354°F on the specimen throughout the duration of the test. When the desired temperatures were reached, the specimen was loaded using a displacement rate of 0.01 in/min. The load-displacement diagram and strain measurements are given in Figures 7-9 for Specimen 2 and Figures 10-12 for Specimen 3. Of the two specimens tested at 350°F, Specimen 2 failed at an ultimate load of 26 kips and Specimen 3 failed at 24 kips. Unlike the room temperature specimen tested, the elevated temperature tests reached an ultimate failure load without any prior load reductions. The ultimate strain measurements ranged from 1641 μ in./in. at the center gauge SG4 to 1354 μ in./in. at gauge SG1 for Specimen 2 and from 1560 μ in./in. at the center gauge SG3 to 1288 μ in./in. at SG6 for Specimen 3. Also, unlike the room temperature test where all three bolt hole locations displayed bearing damage, both elevated temperature specimens showed significant bearing damage only at the center and one side bolt hole with almost no visible bearing damage at the third bolt hole location. A non-uniform distribution of the load between fasteners would partially attribute to the strength reduction for the elevated temperature test specimens.

A summary of the single row joint test results is presented in Table 2. With an increase in test temperature from room to 350°F, a 37% decrease in the specimen strength capacity was observed. All single-row joint specimens tested failed in a bearing mode.

Table 2. Single-row Joint Tension Testing Summary

Joint Specimen	Test Temperature (°F)	Failure Load (kips)	Failure Mode
1	70	40	Bearing
2	350	26	Bearing
3	350	24	Bearing

Multi-row Joint

The multi-row splice joint specimens were fabricated to be 5.55 inches in width, 29.55 inches in length, and were designed to transfer 111 kips of applied tensile loading. Three PMC to PMC specimens and three PMC to SPF/DB specimens were fabricated where two of each configuration were

to be tested in static tension and the remaining two were to be tested in fatigue. A sketch of a PMC to PMC joint specimen and a sketch of a PMC to SPF/DB specimen, including strain gauge locations, are given in Figures 13 and 14, respectively. As can be observed in the figures, both joining components were tapered down under the outer splice plate to provide a smooth aerodynamic surface between the splice plate and joining components. On the inner (spar) side, the PMC to PMC specimen was designed with a flat inner splice plate and the PMC to SPF/DB specimen had a tapered T-section inner splice plate. The tapering splice plate design was included to provide a more uniform fastener load distribution. A photograph of the two specimens is shown in Figure 15 where a top view (outer wing surface side) of a PMC to PMC specimen and a bottom view (wing spar side) of a PMC to SPF/DB specimen are shown.

The PMC to PMC specimens were instrumented with 22 back-to-back strain gauges as shown in Figure 13. On each side, five gauges were located across the center of the splice plates and three were located on each composite sandwich about 1.5 inches from the edge of the splice plate. The PMC to SPF/DB specimens had a total of 17 strain gauges as shown in Figure 14. On the outer splice plate, five gauges were located across the center as on the PMC to PMC specimen. Three back-to-back gauges were located on the PMC sandwich about 2 inches from the edge of the splice plate. On the SPF/DB component, four gauges were located on the outer surface and two on the inner surface. The two back-to-back gauges were located 0.4 inch from the edge of the splice plate and the other two gauges on the outer surface were located about 2.5 inches from the splice plate.

Static Tension Testing

All four static tension tests were conducted using the same fixtures for connecting the test specimen to the 220 kip test machine. A photograph of one of the PMC to SPF/DB specimens mounted in the test machine is shown in Figure 16. The specimen fixtures were designed and fabricated at NASA Langley Research Center. Two steel plates are attached on each end of the specimen by five steel 0.5 inch diameter bolts. The steel plates are also attached to the test fixture through a pin connection on each end as pointed out in Figure 16. Back-to-back horizontal knife edge supports are used to prevent out-of-plane displacement along the centerline of the test specimen while it is being loaded in tension. Without this constraint, there would be significant out-of-plane motion under tensile loads due to eccentricities in the specimen as was revealed by a finite element analysis of the test specimen.¹

The room temperature tests were conducted with the test machine set on stroke control with an applied displacement rate of 0.04 in./min. The applied load and displacement were monitored during testing and testing continued until ultimate failure occurred, which is defined here as a 20% decrease in the applied load. The load-displacement graph for the PMC to PMC joint specimen tested at room temperature is shown in Figure 17. As can be observed in the figure, the load continued to increase until ultimate failure at 137 kips applied load. A gradual decrease in the slope near failure indicates plastic behavior prior to ultimate failure. Ultimate failure appeared to be a consequence of shearing

¹ Finite element analysis was performed by Young Kwon at Lockheed Georgia.

off of the fastener head. A photograph of the failed specimen is given in Figure 18. During loading, an audible "crack" was identified at 61 kips and splice plate bending induced by fastener bending became visible at 120 kips applied load. Examination of the failed specimen after removing the splice plates showed significant bearing damage in the composite sandwich. Back-to-back strains measured at the center of the specimen splice plates are shown in Figure 19. The back-to-back strain gauges SG17 and SG18 were at the center and SG13 and SG22 were closest to the edge as indicated in Figure 13. The maximum strain measured at failure was 14,174 $\mu\text{in./in.}$ at SG17 in the center. However, the strain measured at SG17 was suspiciously higher than the surrounding strain gauges, raising the issue that SG17 may be defective. The next largest strain next to SG17 was 8871 $\mu\text{in./in.}$ measured by SG15 where SG19 on the other side of SG17 measured 8823 $\mu\text{in./in.}$ Back-to-back strains measured on the composite are shown in Figure 20. The minimum strain measured was 4277 $\mu\text{in./in.}$ by SG6 on the composite. The load-displacement graph for the PMC to SPF/DB specimen tested at room temperature is shown in Figure 21 and a photograph of the failed specimen is shown in Figure 22. An ultimate load of 123 kips was observed and the ultimate failure appeared to be due to a tension failure of the inner splice plate along the outer row of fasteners. Bending of both splice plates was apparent in the failed specimen as can be observed in Figure 22. Examination of the failed specimen after removing the splice plates revealed no visible sign of bearing damage in the PMC to SPF/DB specimen. During loading, at 70 kips an audible "crack" was heard and as with the PMC to PMC specimen, outer splice plate bending was also observed at 92 kips applied load. Measured strains are plotted as a function of applied load in Figures 23-25. Figure 23 shows the measured strains on the center of the upper splice plate (SG3 was at the center and SG1 and SG5 were the outer most strain gauges as can be seen in the sketch in Figure 14). Figure 24 shows strains measured on the SPF/DB component and Figure 25 shows strains measured on the PMC sandwich component. At approximately 70 kips applied load, the load where the audible "crack" was heard, Figure 25 reveals an almost instantaneous drop in the strains on one PMC facesheet with a corresponding instantaneous increase in the strains on the opposing facesheet. The cause for this behavior is uncertain, but it could possibly be attributed to a very localized failure of the inner PMC facesheet which caused the outer facesheet to accept a localized instantaneous increase in load and consequently strain. As also revealed in Figure 25, the subsequent instantaneous strain increase in the inner facesheet at approximately 114 kips is also uncertain, but it may be due to another localized failure resulting in instantaneous redistribution of the load.

For the elevated temperature tests, a Thermatron heater was used to blow hot air through a duct and into an oven that was built to enclose the specimen. The oven box along with a specimen mounted in the test fixture can be seen in Figure 16. The specimens were heated while the test machine maintained a preset load of approximately 100 lbs. Six back-to-back thermocouples were located on the specimen and monitored during heating until a nearly uniform temperature of 350°F was reached. Once acceptable temperatures were achieved, load was applied to the specimens at the displacement rate of 0.04 in./min. During the application of the load to the specimens, the temperatures ranged from 342°F to 352°F on the PMC to PMC joint specimen and from 344°F to 350°F on the SPF/DB to PMC joint specimen. The load-displacement diagram for the PMC to PMC specimen tested at 350°F is given in Figure 26. After an ultimate load of 110 kips was achieved, a 25% increase in the displacement was observed as the load slightly dropped. The specimen was then considered failed and the applied load was removed. Examination of the specimen after testing revealed a slight bending in the splice plates, apparently due to fastener bending. Removal of the splice plates showed significant bearing damage in the composite sandwich as can be viewed in Figure

27. The load-displacement diagram for the PMC to SPF/DB joint specimen tested at 350°F is given in Figure 28. An ultimate load of 105 kips was achieved before the inner splice plate experienced a tension failure at the outer row of fasteners as shown in Figure 29. The appearance of the failed specimen was very similar to the room temperature specimen which also experienced a tension failure of the inner splice plate. After removal of the splice plate, examination of the specimen tested at 350°F showed severe bearing damage in the composite sandwich.

A summary of all the multi-row joint test specimen failure loads is given in Table 3. One can conclude that the PMC to PMC joint has a slightly greater, 10% at room temperature and 5% at 350°F, strength capacity than the PMC to SPF/DB joint. A strength reduction of approximately 15-20% can also be expected for each specimen type at the elevated operating temperature of 350°F.

Table 3. Multi-row Joint Static Test Specimen Failure Loads

Test Temperature (°F)	Failure Load (kips)	
	PMC to PMC	PMC to SPF/DB
70	137	123
350	110	105

Fatigue Testing

The fatigue tests were conducted in the same 220 kip test machine as the static tests. A photograph of the PMC to PMC joint specimen mounted in the test machine is shown in Figure 30. The fixture connecting the specimen to the test machine is shown in the figure. It consisted of back-to-back steel splice plates connected to another steel end fitting in a multifastener arrangement on each end of the specimen. This differs from the static test fixture where a pin connection was utilized. A 50 ft-lb torque was applied to each fastener used in the fixture to prevent slipping at the fixture connection.

The test machine was set in load control to cycle between 33,800 lb in tension and 6760 lb in compression. This was equivalent to an $R = -0.2$, where R is the ratio of minimum applied load to maximum applied load, with the peak load set at approximately 30% of the maximum static design load. The majority of the cycling was conducted at one Hz, which was the maximum cycling rate capability of the test machine. At approximately every 5000 cycles, the test machine cycling was slowed to 0.01 Hz for five cycles to record test data at twice a second.

Both joint specimens tested failed in the same mode, with a transverse crack in the upper splice plate occurring across the inner row of fasteners. The PMC to PMC joint specimen failure occurred at approximately 42,000 cycles and the PMC to SPF/DB joint specimen failed at approximately 31,560 cycles. The splice plate crack was on the PMC side of the joint of the PMC to SPF/DB specimen. During testing of the PMC to PMC specimen, out-of-plane bending of the top splice plate was observed where the outer edges were observed to curve out away from the joint. There was also an audible "crackling" sound present throughout the duration of the test. Load versus displacement data are plotted in Figure 31. Shown is the load versus displacement test data during the first five cycles that were recorded and the last five cycles that were recorded prior to failure. At failure, which occurred at approximately 42,000 cycles, a change in slope in the load-displacement real time plot was observed with a progressively decreasing slope for several cycles prior to stopping the test. Load versus displacement test data for the PMC to SPF/DB joint specimen is shown in Figure 32. Once again, the load and displacement test data during the first set of five cycles that was recorded and the last set of five cycles that was recorded prior to failure is displayed. During testing of the PMC to SPF/DB joint specimen, the doubler that was adhesively bonded on the bottom side of the SPF/DB component at the location of the taper on the top side of the component, became disbonded from the specimen and fell off the specimen at approximately 15,000 cycles. Overall out-of-plane bending motion of the specimen was also more pronounced during cycling than that observed with the PMC to PMC joint specimen. The lower fatigue life for the PMC to SPF/DB joint specimen might be attributable to the increased bending motion. Unfortunately, both fatigue tests resulted in fatigue lives much shorter than the 100,000 cycles predicted for the joint. Removal of the splice plates after testing revealed no visible damage to the joint components in either fatigue specimen. A summary of fatigue test results are shown in Table 4.

Table 4. Multi-row Joint Fatigue Test Summary

	PMC to PMC	PMC to SPF/DB
Fatigue Life, N	42,335	31,568
First 5 Cycles Recorded	1541-1545	1-5
Last 5 Cycles Recorded	41541-41545	30001-30005

Concluding Remarks

Composite sandwich splice joint element testing to verify the strength and fatigue life of the specimen designs has been completed. Both single-row composite honeycomb sandwich and multi-row composite honeycomb sandwich splice joint specimens were tested at both room temperature and an elevated operating temperature of 350°F.

For the single-row joint specimens tested, the room temperature test failure load exceeded the design ultimate load, however, the elevated temperature tests resulted in failure loads below the room temperature design load. All specimens failed in a bearing mode with an approximately 30% reduction in strength capacity at the elevated operating temperature of 350°F.

Similarly with the multi-row composite honeycomb sandwich splice joints tested statically, the room temperature test failure loads exceeded the design ultimate load, and the elevated temperature test failure loads were slightly lower than the room temperature design load. For the PMC to PMC joint specimens tested, the room temperature ultimate failure mode was due to fastener head shear off. At the elevated test temperature, a 20% reduction in the strength capacity and a change in the failure mode due to bearing damage was observed. However, bearing damage was observed in both specimens tested. For the PMC to SPF/DB splice joint tested, both the room and elevated temperature tests exhibited the same ultimate failure mode where an inner splice plate tension failure occurred at the outer row of fasteners. A 15% reduction in strength was observed for the elevated temperature test. Although there was no bearing damage observed for the room temperature specimen, significant bearing damage was present in the elevated temperature PMC to SPF/DB test specimen.

Fatigue testing at a maximum tensile load of 33.8 kips with an R=-0.2 of the multi-row joint specimens resulted in a fatigue life of 42,000 cycles for the PMC to PMC joint specimen and a fatigue life of 31,500 cycles for the PMC to SPF/DB joint specimen tested. Both specimens failed due to a tension crack at the inner row of fasteners on the outer splice plate. The fatigue lives achieved for these tests were lower than the predicted fatigue life of 100,000 cycles.

References

1. Hou, T.H.; Jensen, D.J.; and Hergenrother, P.M.: Processing and Properties of IM7/PETI composites. *Journal of Composite Materials*, Vol. 30, Issue 1, January 1996, p.109-12.

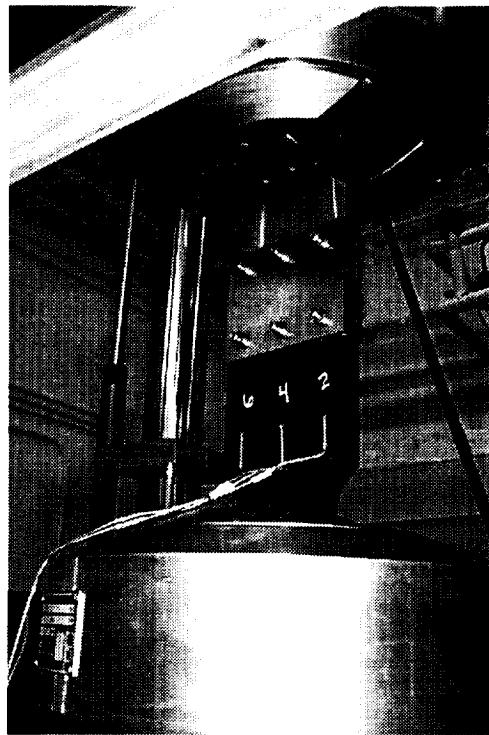


Figure 1. Single-row joint specimen mounted in test machine using hydraulic grips for the room temperature test.

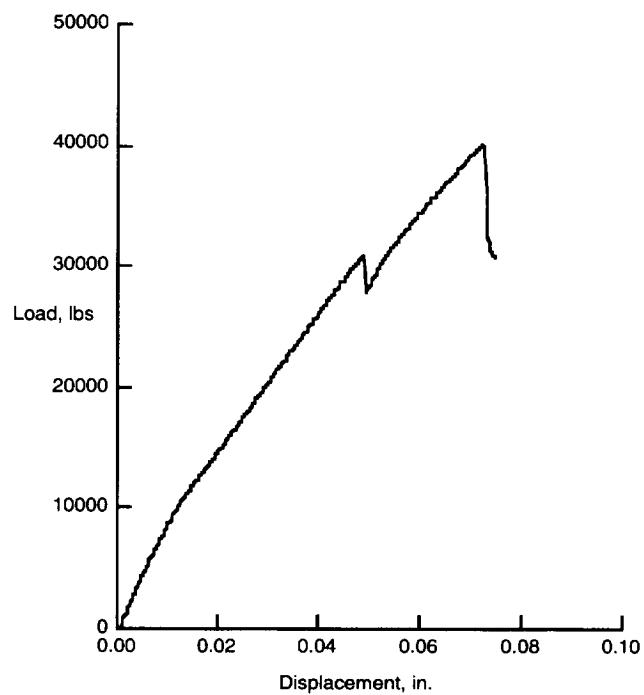


Figure 2. Load versus displacement for the room temperature single-row joint test.

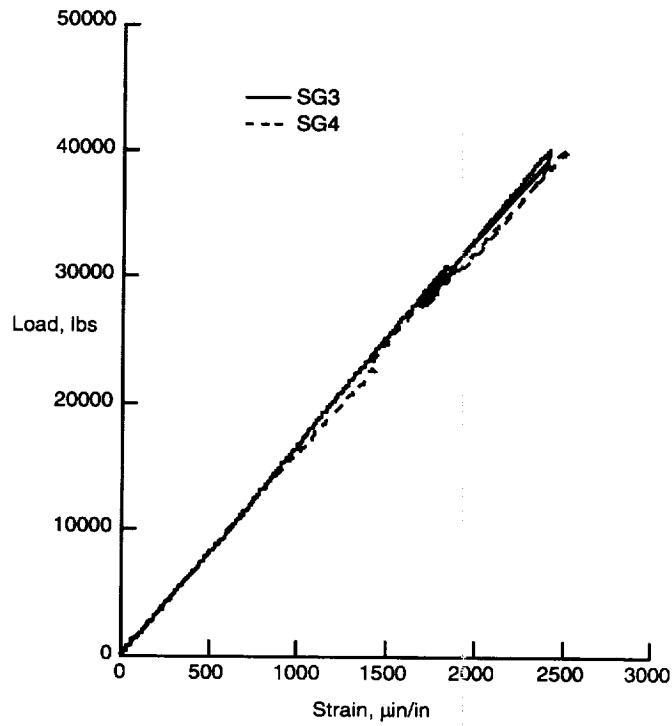


Figure 3. Back-to-back measured strains at the center of the room temperature joint specimen.

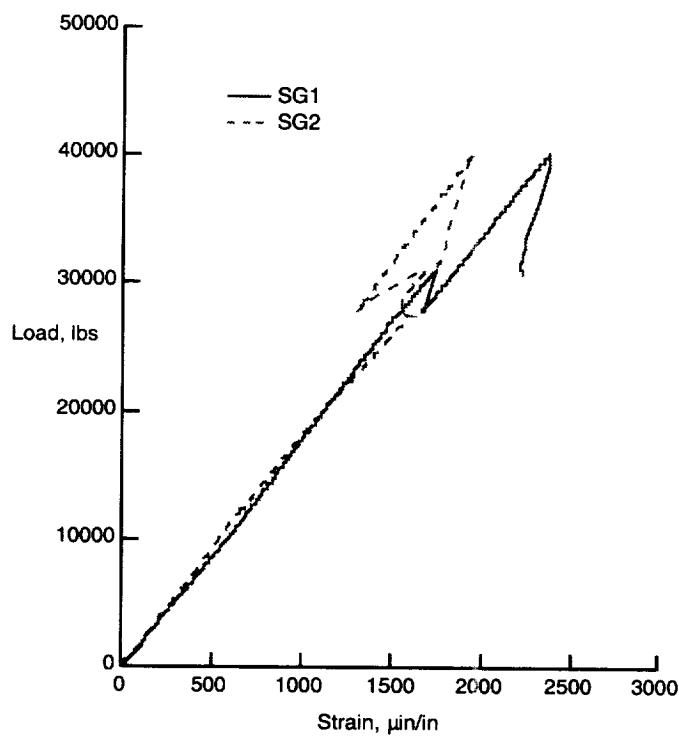


Figure 4. Measured strains from strain gauges SG1 and SG2 of the room temperature joint specimen.

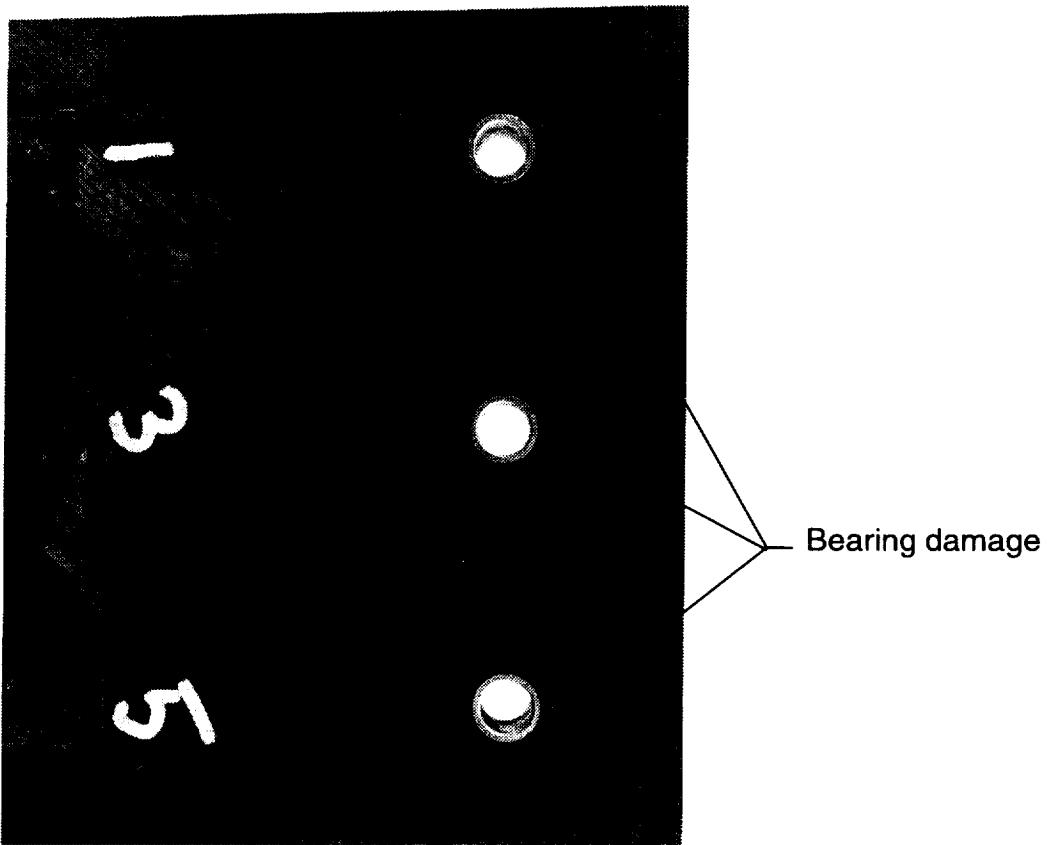


Figure 5. Single-row joint Specimen 1 after testing to failure.



Figure 6. Single-row joint specimen mounted in test machine for elevated temperature testing.

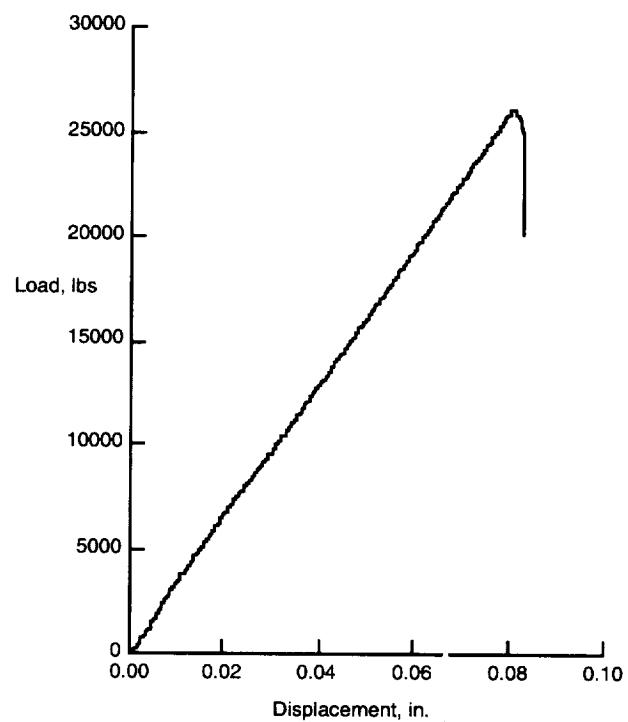


Figure 7. Load versus displacement for Specimen 2 tested at 350°F.

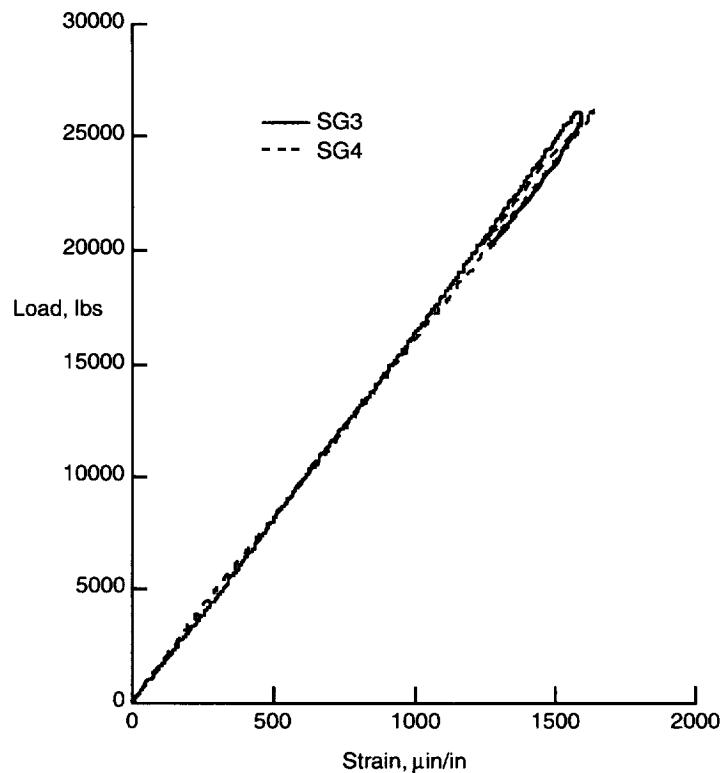


Figure 8. Back-to-back measured strains at the center of Specimen 2 tested at 350°F.

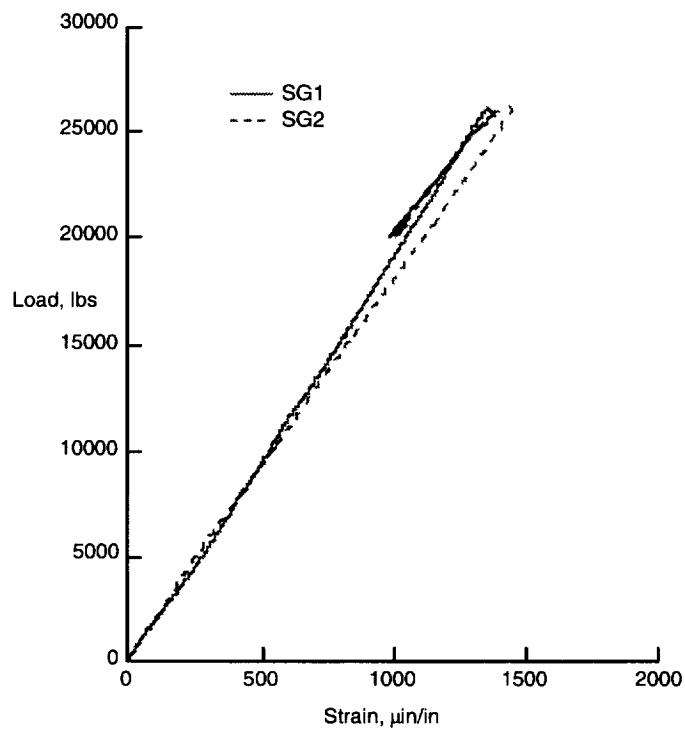


Figure 9. Measured strains from strain gauges SG1 and SG2 on Specimen 2 tested at 350°F.

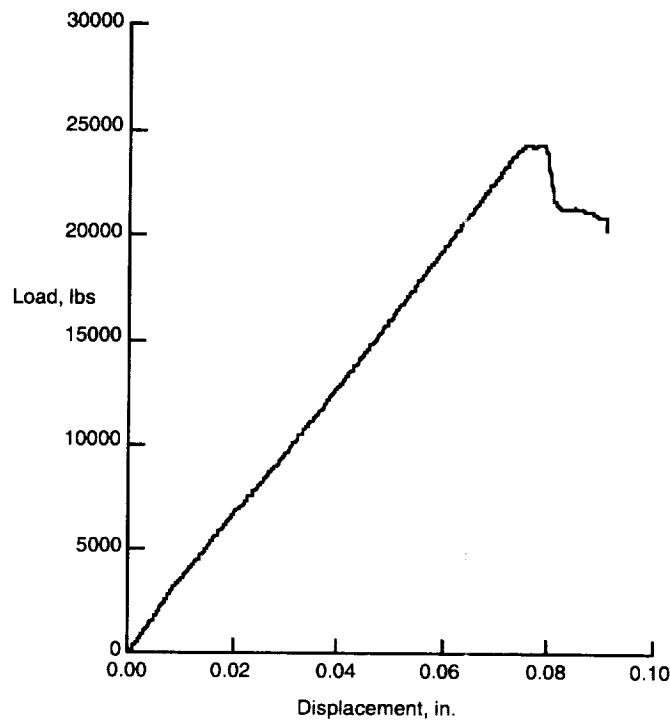


Figure 10. Load versus displacement for Specimen 3 tested at 350°F.

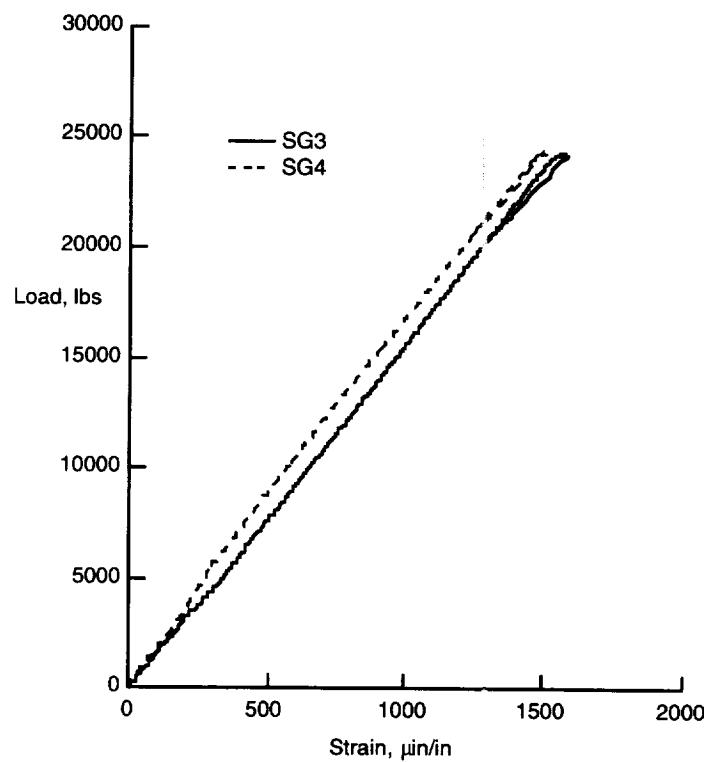


Figure 11. Back-to-back measured strains at the center of Specimen 3 tested at 350°F.

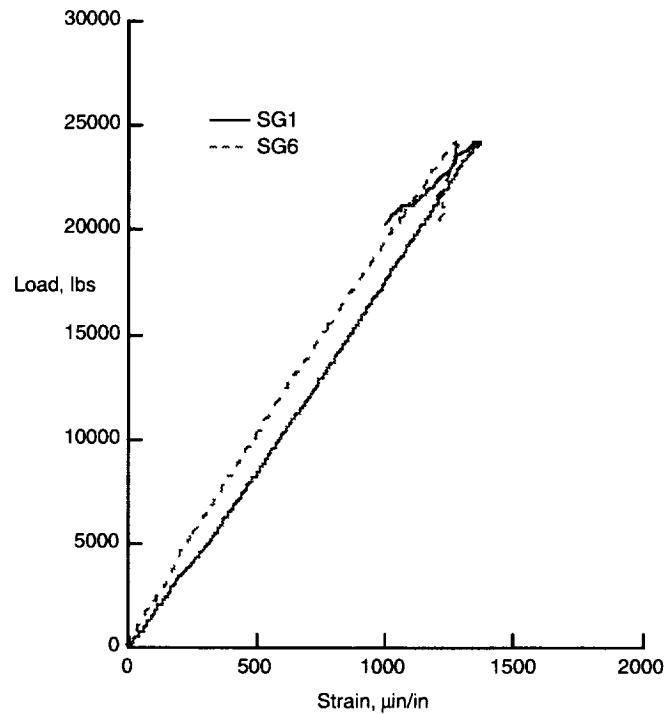


Figure 12. Measured strains from strain gauges SG1 and SG6 on Specimen 3 tested at 350°F.

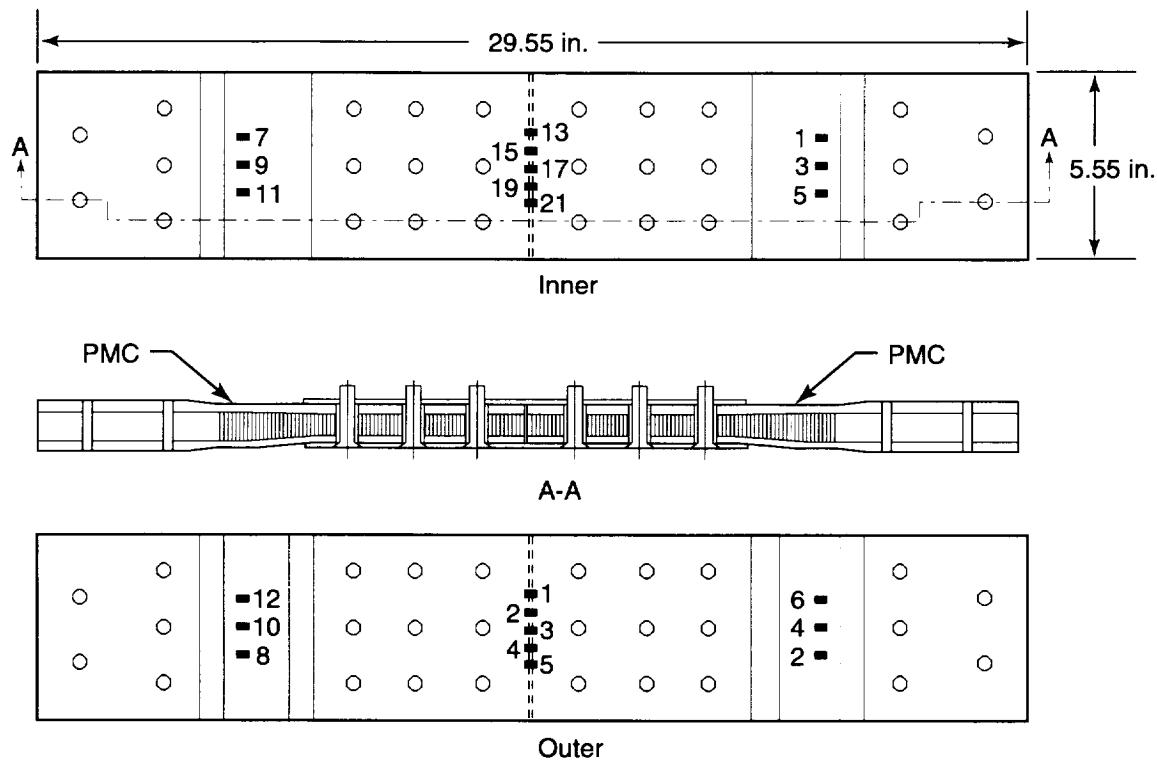


Figure 13. Schematic drawing of PMC to PMC multi-row joint specimen including strain gauge locations.

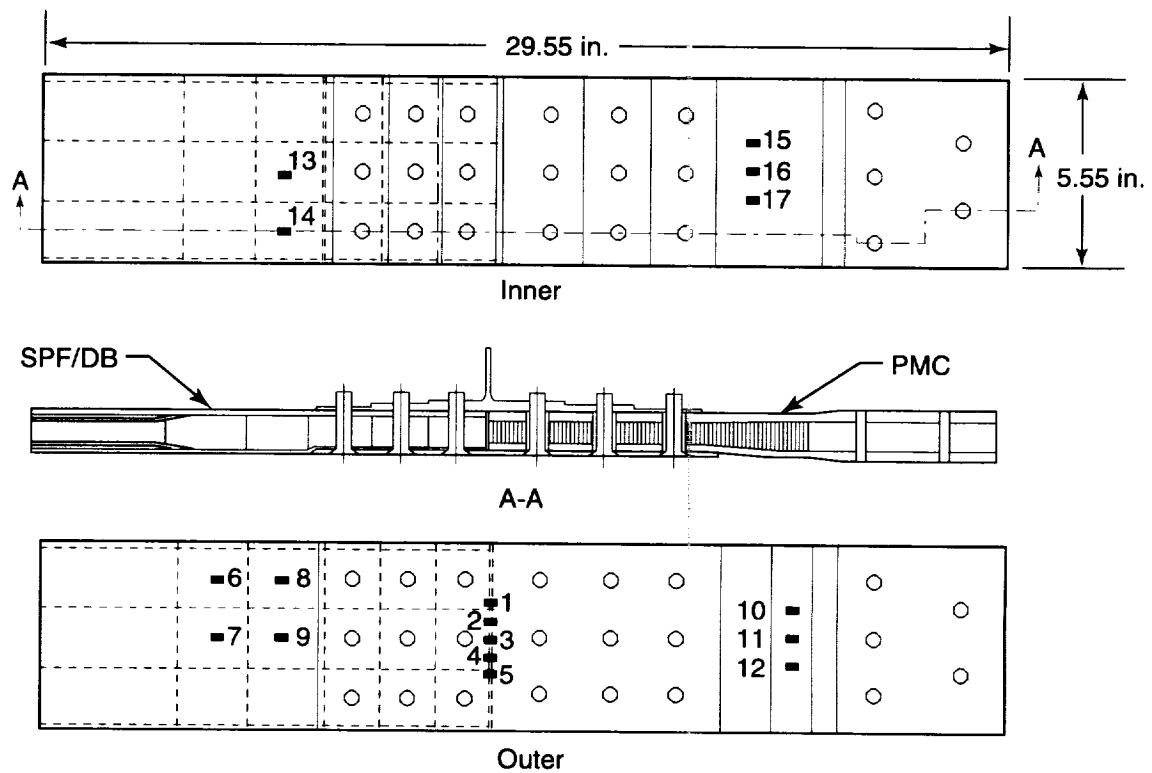


Figure 14. Schematic drawing of PMC to SPF/DB multi-row joint specimen including strain gauge locations.

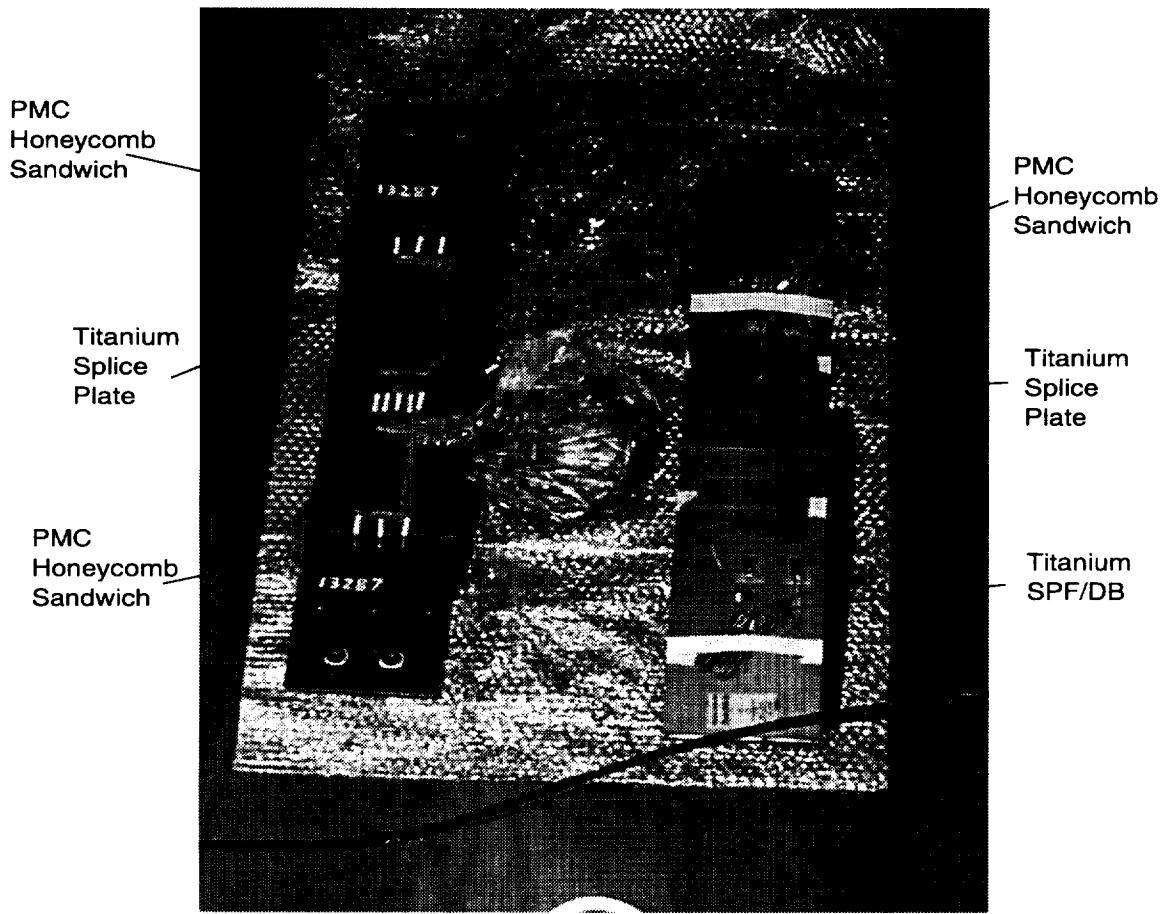


Figure 15. Multi-row joint test specimens.

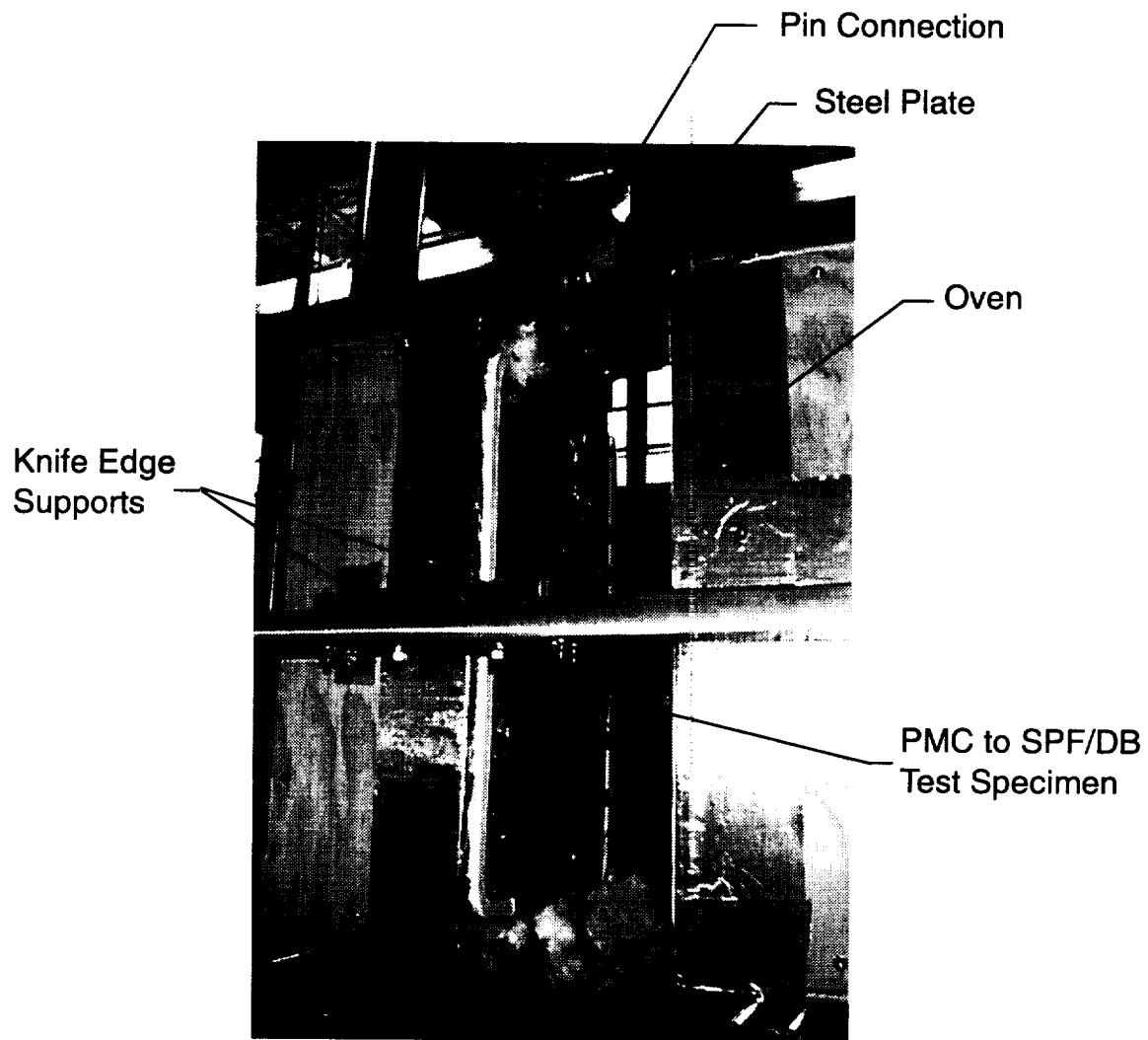


Figure 16. Multi-row joint static tension testing configuration.

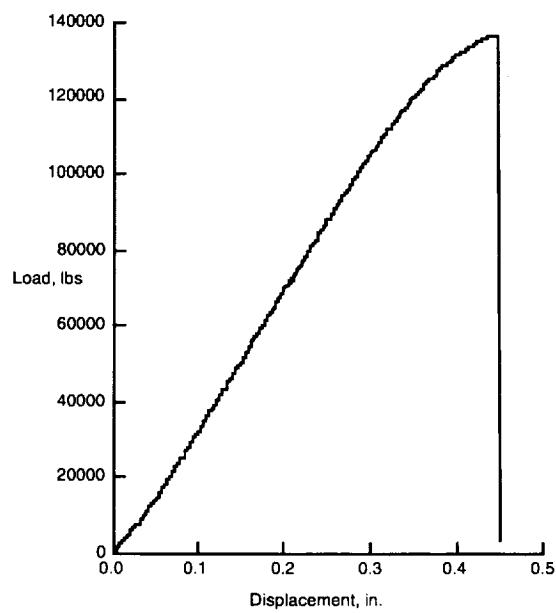


Figure 17. Load versus displacement of the PMC to PMC joint specimen tested at room temperature.

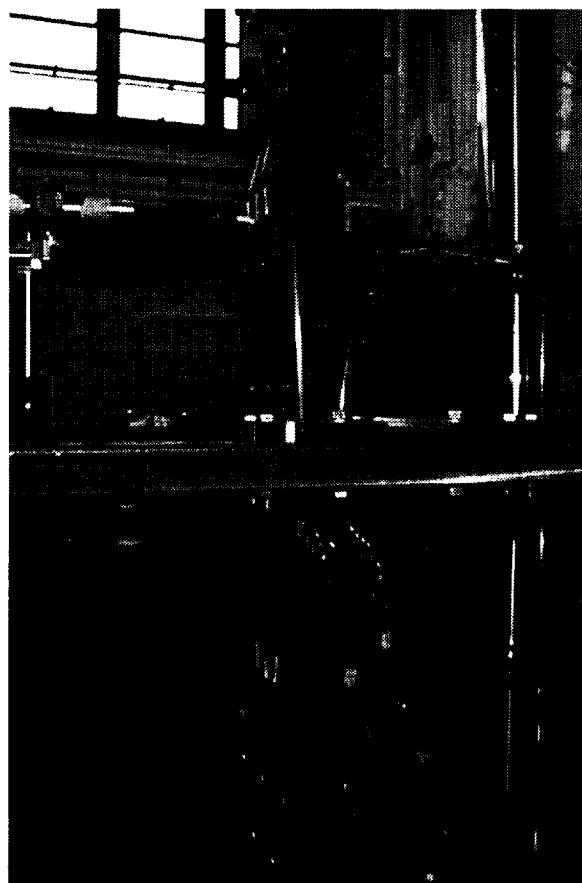


Figure 18. Failed PMC to PMC joint specimen tested at room temperature.

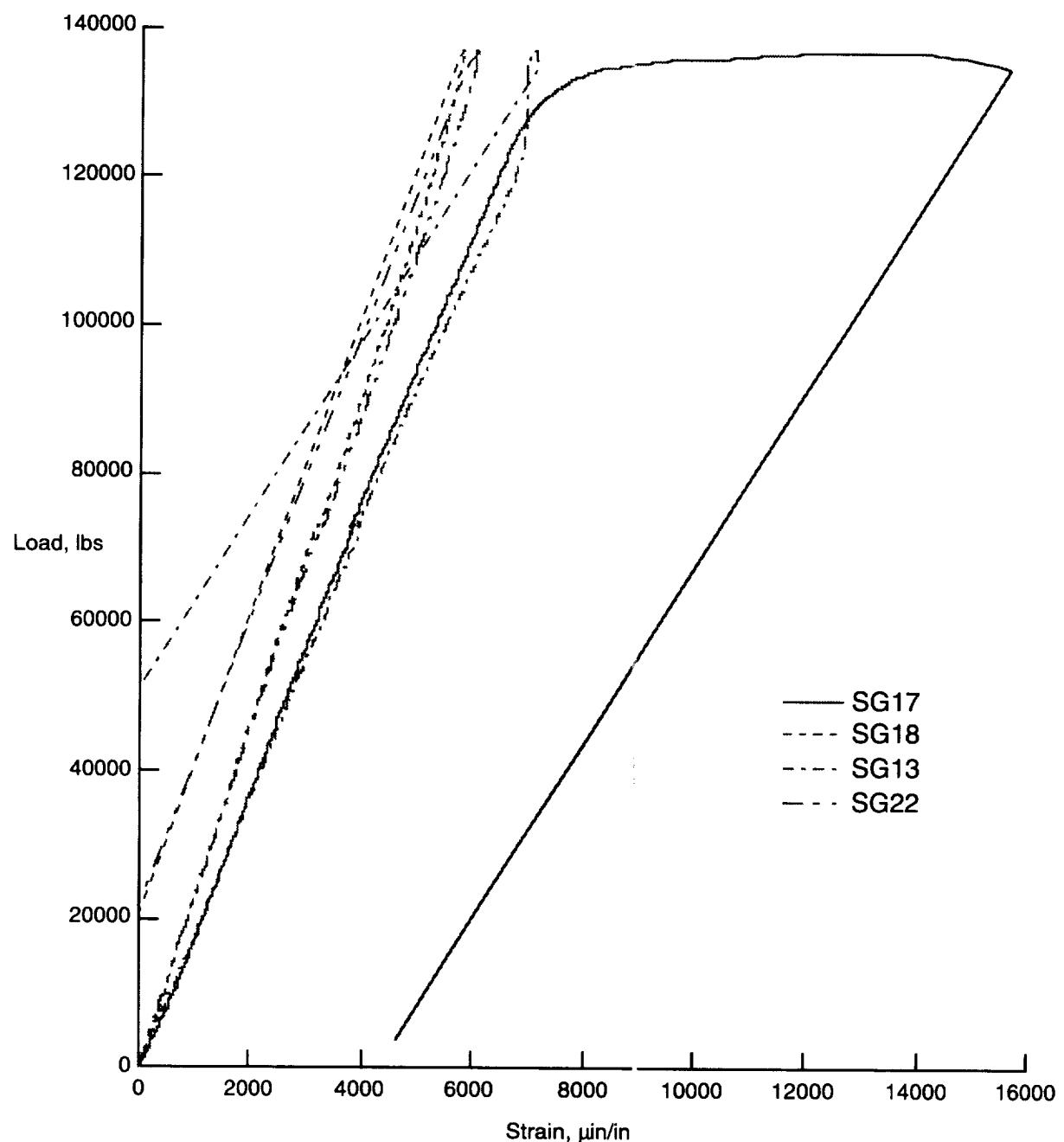


Figure 19. Strains measured at the center of the splice plate for the PMC to PMC joint specimen tested at room temperature.

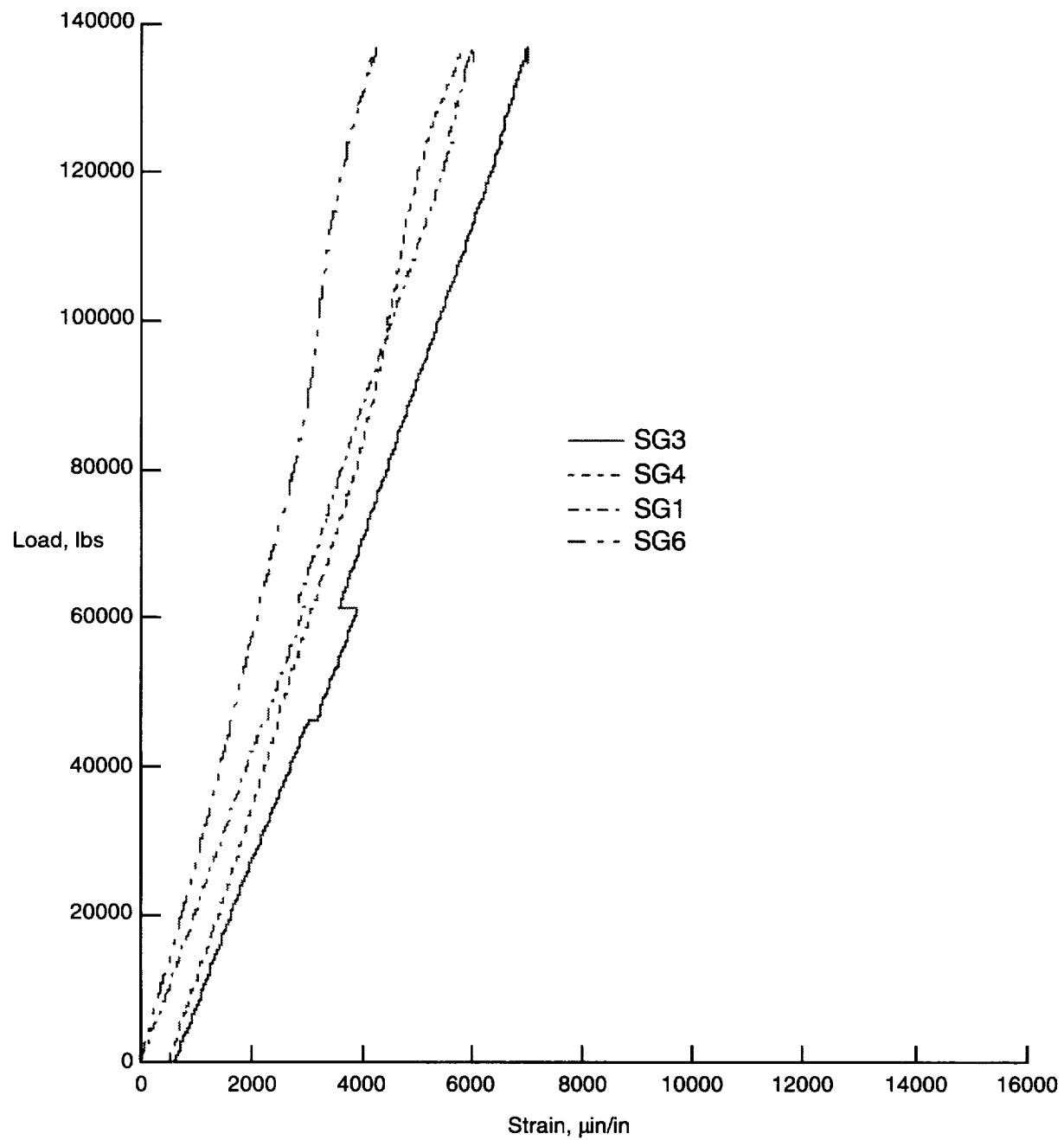


Figure 20. Strains measured on the composite sandwich for the PMC to PMC specimen tested at room temperature.

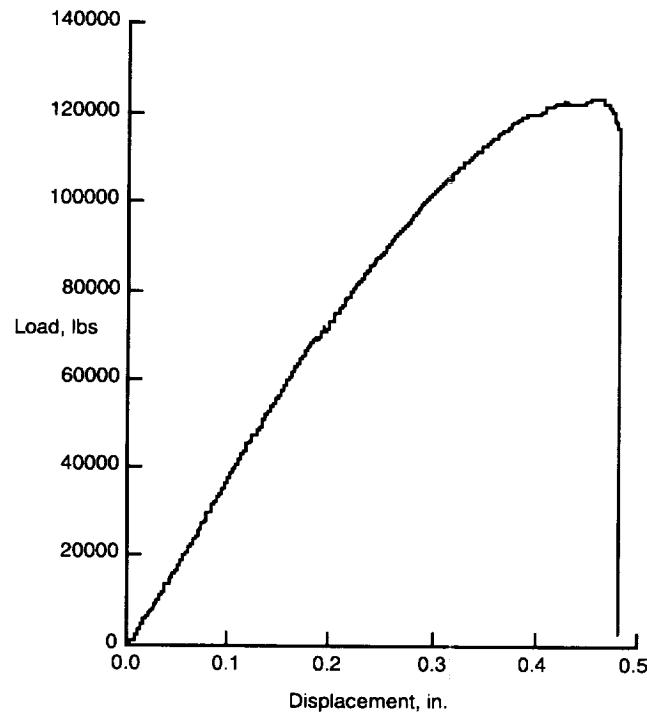


Figure 21. Load versus displacement for the PMC to SPF/DB joint specimen tested at room temperature.

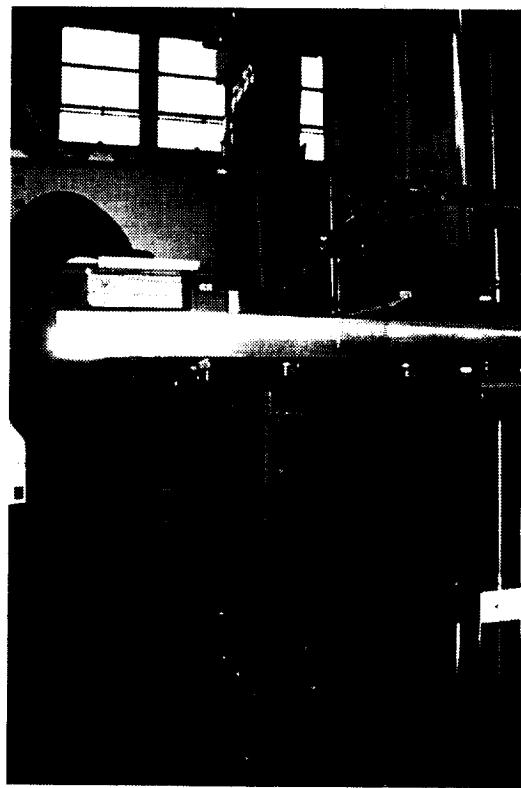


Figure 22. Failed PMC to SPF/DB specimen tested at room temperature.

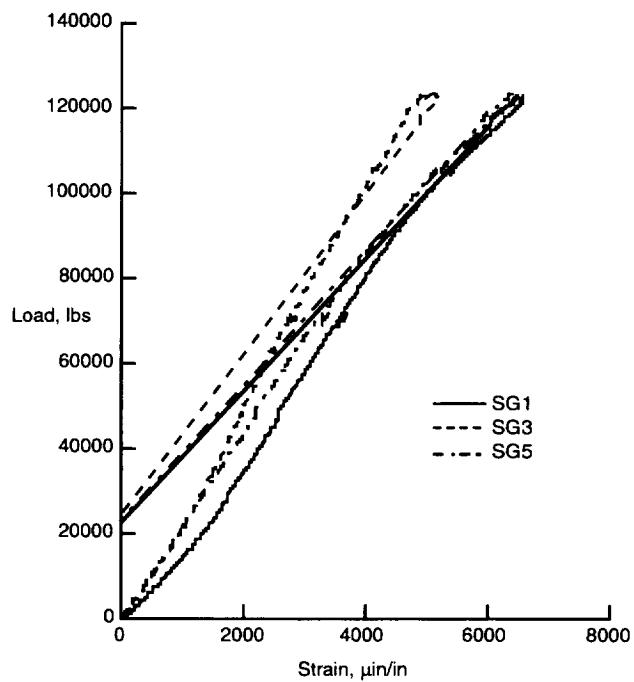


Figure 23. Strains measured at center of top splice plate for the PMC to SPF/DB joint specimen tested at room temperature.

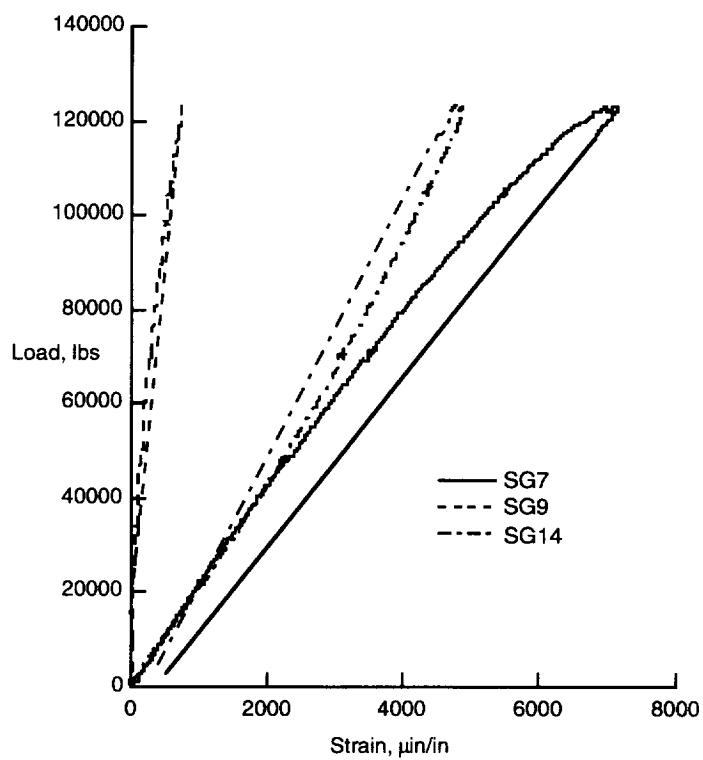


Figure 24. Strains measured on the SPF/DB component for the PMC to SPF/DB joint specimen tested at room temperature.

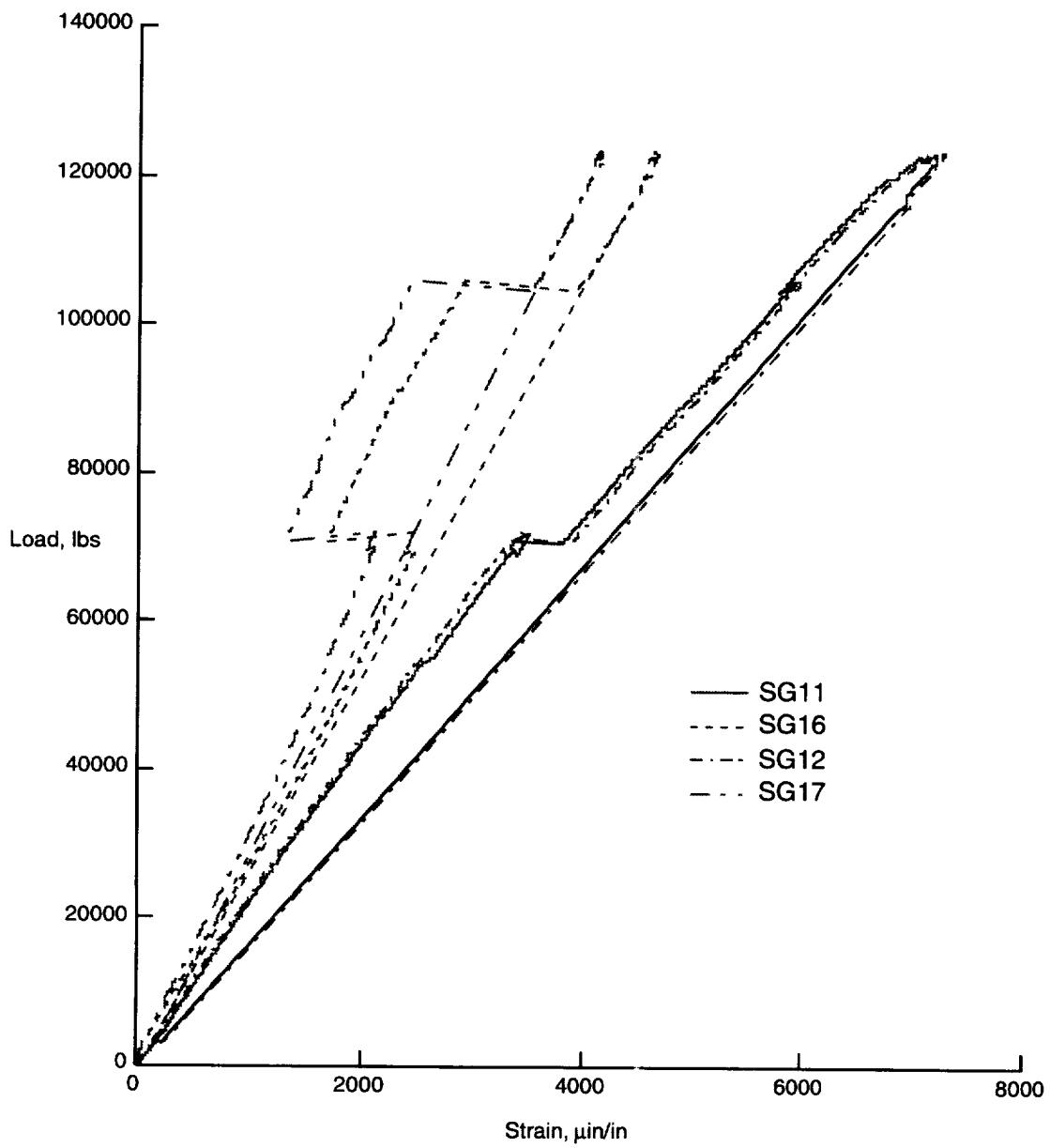


Figure 25. Strains measured on the PMC sandwich component for the PMC to SPF/DB joint specimen tested at room temperature.

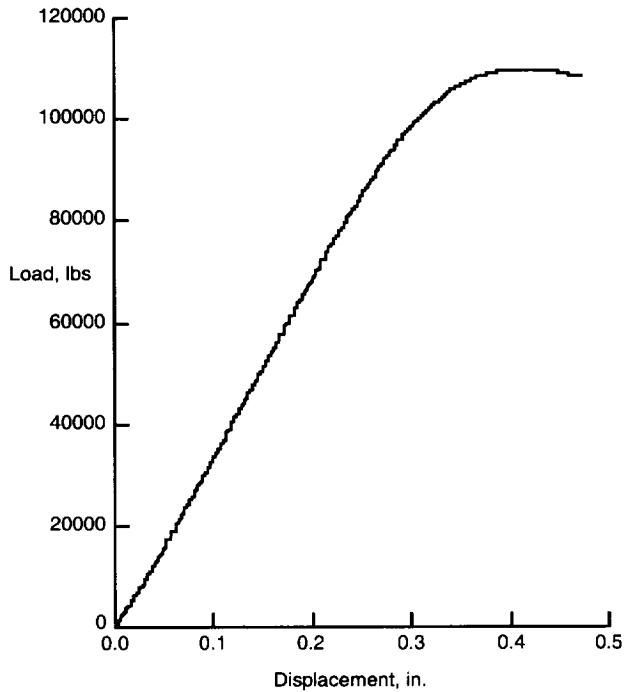


Figure 26. Load versus displacement for the PMC to PMC joint specimen tested at 350°F.

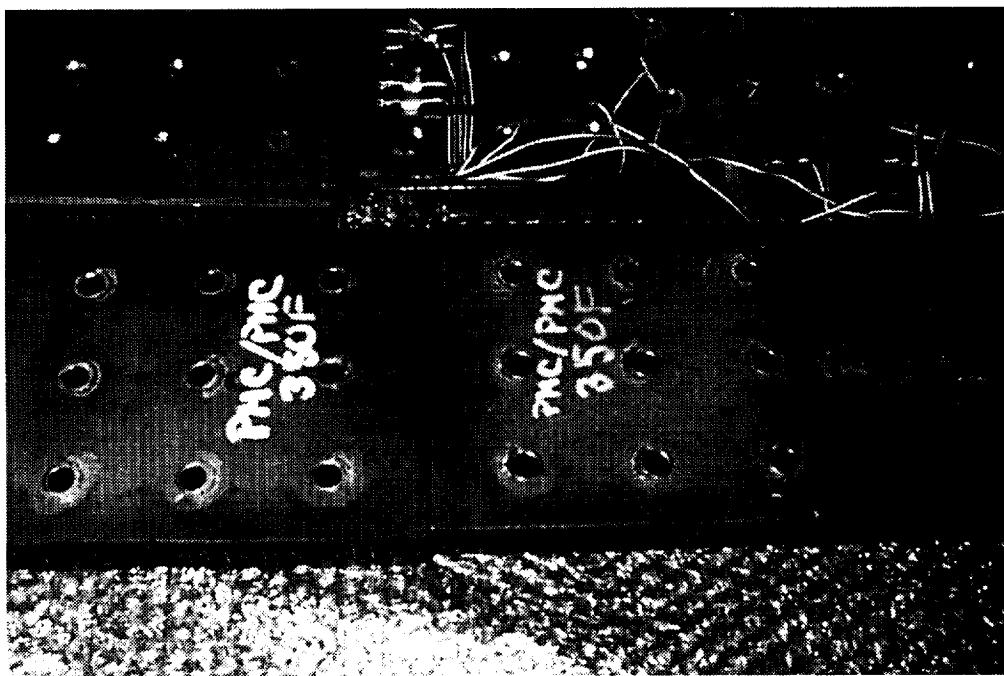


Figure 27. PMC to PMC joint specimen after testing at 350°F and having the splice plates removed for examination of the composite sandwich components.

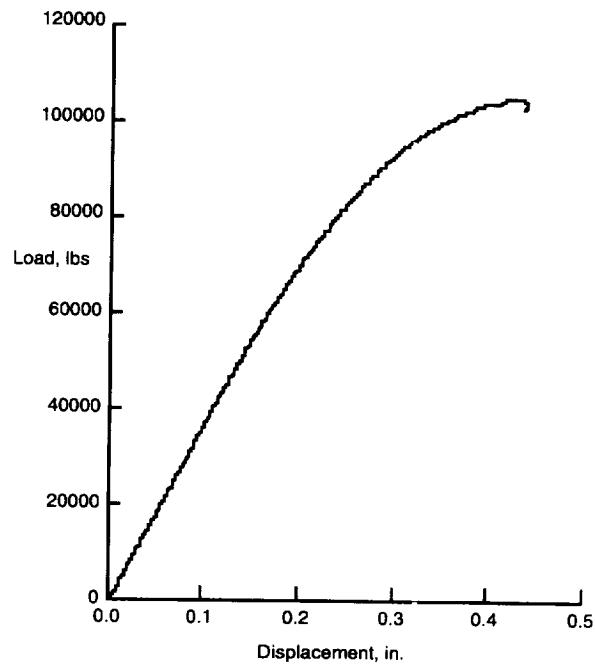


Figure 28. Load versus displacement for the PMC to SPF/DB joint specimen tested at 350°F.



Figure 29. Failed PMC to SPF/DB joint specimen tested at 350°F.

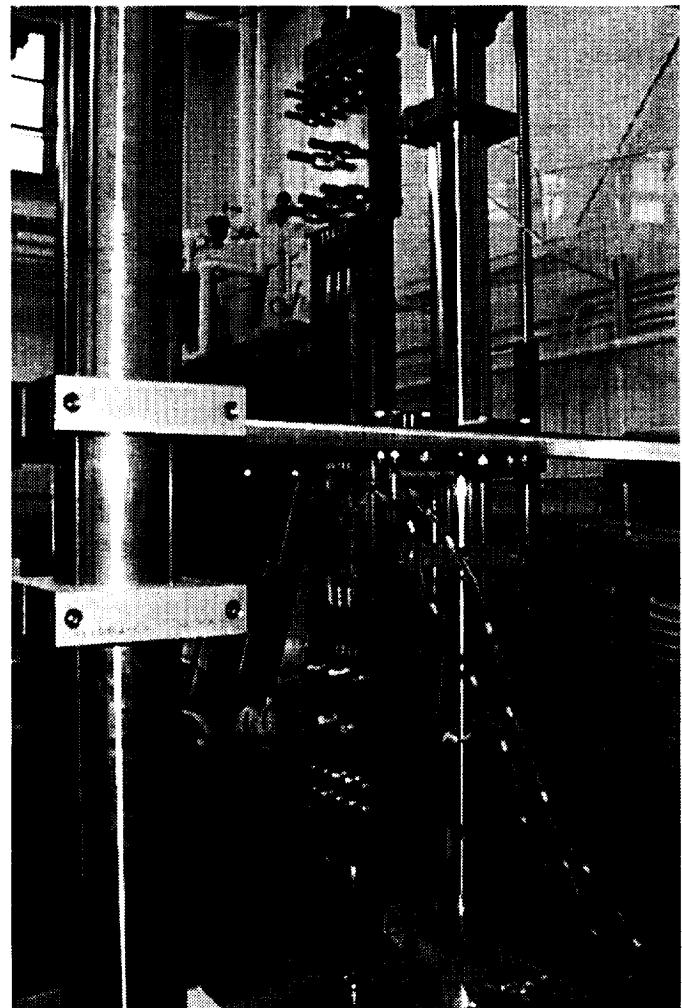


Figure 30. PMC to PMC joint specimen mounted in test machine for fatigue testing.

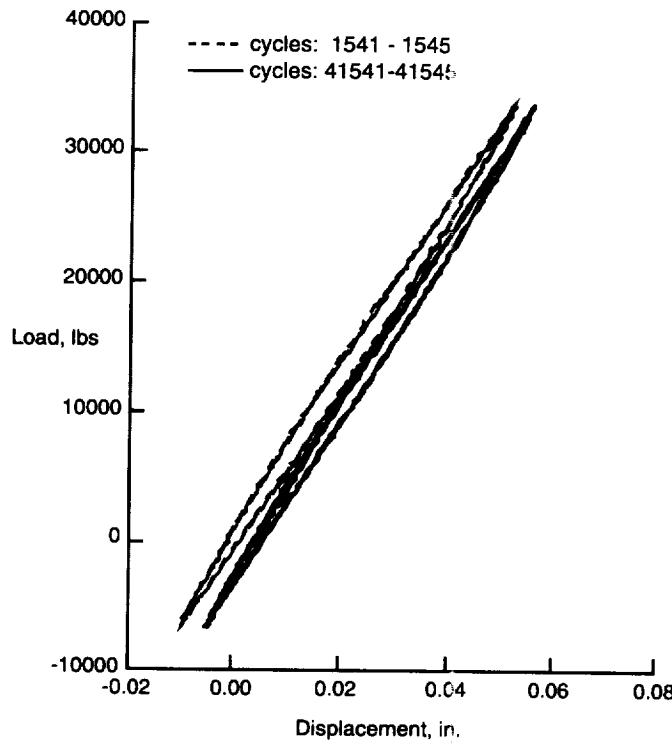


Figure 31. Load versus displacement test data for the PMC to PMC joint specimen tested under cyclic loading.

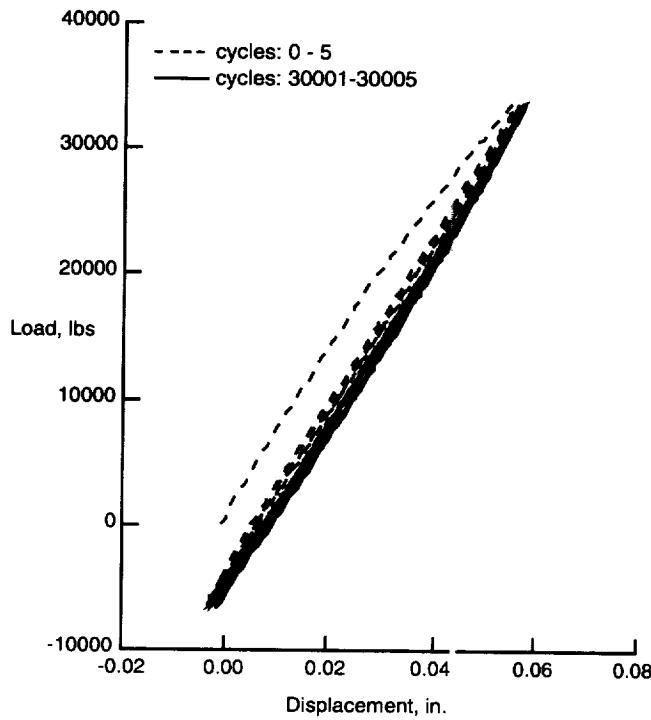


Figure 32. Load versus displacement test data for the PMC to SPF/DB joint specimen tested under cyclic loads.

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